Chapter

Roles of Terpenoids in Essential Oils and Its Potential as Natural Weed Killers: Recent Developments

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Abstract

Weed control through the use of conventional chemical compounds presented by synthetic herbicides is a widely used and successful method to control weed by reducing the negative impact of weed and increase agricultural production gradually. However, although the losses in agricultural production arising from weed competition are decreased through the use of synthetic herbicides, the negative impacts of these compounds on the environment and human health have raised awareness and created grave concern of a number of parties to safeguard the environment and humans. The adverse effect of synthetic herbicides can still occur even if such herbicides are applied at the recommended rates. Control weed naturally presented by allelochemical compounds provides an attractive, alternative and safe way to control weed synthetic herbicides. Previous works indicated that terpenoids as the most important group of allelochemicals have shown to exhibit a good phytotoxic effect against a wide range of weed species by suppressing germination and reducing growth. This review was a highlight to detect the desirable phytotoxic effects of some terpenoid compounds as a major content in essential oils on various weed species and the possible uses as natural weed killers.

Keywords: essential oils, terpenoids, allelochemicals, weeds, natural killers

1. Introduction

Weed control defined as any method trying to stop weeds, especially noxious or injurious weeds from competing with desired plants. The evolution of weed control began many years ago when humans felt that it was necessary to remove and dispose of weeds in order to reduce their competition with the planted crops and thereby increase the yield qualitatively and quantitatively. Weed control involves processes where weed infestations are reduced, but not necessarily eliminated. In weed control, the degrees of control can be described by the state of weed reduction ranging from poor to excellent. The degrees of control depending on the types of weeds involved and the effectiveness of the control method adopted. It should be noted that in weed control, the weeds are generally not completely killed, however, their growth is somewhat contained while the crop continues a normal yield. Weed control is aimed at only reducing the weeds present by employing some form of control measures. On the contrary, weed management is a systematic approach where the whole land use planning is carried out in advance to minimize the very invasion of weeds in aggressive forms and give crop plants a strong competitive advantage over the weeds. Weed control methods can be grouped into the culture, physical, biological and chemical [1]. Human efforts of controlling weeds began with the use of cultural practices such as tillage, planting, crop rotation, fertilizer application, irrigation, etc., that are adapted to create favorable conditions for the crop. If properly used, the practices can help in suppressing weeds. On the other hand, culture methods alone, cannot control weeds; it can only help to reduce the weed population. Culture methods therefore, can be effectively used in combination with other methods. Every method of weed control has its own advantages and disadvantages. No single method is successful under all weed situations. Most often, a combination of these methods gives effective and economic control than a single method. These methods of controlling weeds were later developed in the form of mechanical weed control such as hand pulling, hand hoeing, and planting in rows to facilitate machinery use, but again these methods did not attain the desired benefits [2].

Later, a new mechanism of weed control was developed through the use of chemical inputs. Chemical weed control began on a small scale. Since the 19th century, a combination of salt and ash powder was used to control weed plants which grow on either side of the railway. The use of synthetic herbicides, however, begun in the 1940s with the development of some organic herbicides, specifically the 2,4-D. This herbicide is considered as a growth regulator used in high doses to control broadleaf weeds [3]. Then, chemical weed control was widely used as a form of weed control and achieved a dominant role in the crop management, more efficient, economical and low costs as compared to other methods and contributed strongly to the increase in the agricultural yields and reduce losses due to weeds [4, 5]. As a result of using chemical weed control, the traditional method of weed control such as cultivation and hand weeding has been greatly been decreased [6]. A new method to control weeds was created by producing different types of synthetic herbicides according to the mode of action of these compounds against weed plants. By 1990s, the number of compounds that have been used in herbicides in many different formulas reached to more than 180 compounds [7]. According to a report of [8], the total value of the global's agrochemical market was between 31 and 35 billion US$ and of the products, herbicides accounted for 48% followed by fungicides at 22%. Nowadays, chemical weed control becomes as an integral part of the complex world of technical inputs required for modern agricultural production and have been accepted as a standard tool of the trade by farmers throughout the world despite the negative effects of synthetic herbicides on the ecosystem [1].

2. Negative impacts of the synthetic herbicides on human health and ecosystems

Although synthetic herbicides are considered the best and effective methods to be used as weed control, the risk is very high if it is used indiscriminately. The types, quantity and frequency of applications of the synthetic herbicides can bring about various harmful effects to the environment and its ecosystems and in fact a threat to human health. The uses of synthetic pesticides including herbicides have directly and indirectly brought about several adverse effects to the soil surface, groundwater and organisms as well as in the atmosphere. The above changes have negative ramifications for the community and disrupting the ecological balance, hence risking human life.

2.1 Human health

There is no segment of the population that is completely protectedc exposure and high risk groups are not only of the people of the developing countries but all the countries over the world. The hazards of synthetic pesticides are summarized by their impact through food commodities, surface water, groundwater and soil contamination and the effects on soil fertility (beneficial soil microorganisms) and non-target vegetation [9]. According to the report of Williams et al. [10] also highlighted the complaint of contacts diseases, acute ulcer, heart pain, skin rashes respiratory condition and eye problem of the people in the survey area. In another study conducted by Niemann et al. [11] on glyphosate; a common non-selective systemic herbicide promoted by the manufacturers as a safer herbicide, reported tracing of its residues in both humans and animal urine. It was then suggested that the use of glyphosate may have to be re-evaluated to reduce human exposure to the dangers of synthetic herbicides.

2.2 Ecosystems

Using synthetic herbicides even at recommended rates can lead to negative impacts on the ecosystems, especially the harmful effects that come from their residues. On the other hand, the efficiency of these compounds will be slowly decreased due to the increase in the resistance of the weed plants as a result of the continuous use of these compounds to control the same weed species. Hence, using these synthetic herbicides continuously becomes a double-edged sword. As it is well known, the insecticides are the most toxic to the environment, followed by fungicides and herbicides. But there are some herbicides that can be highly toxic and much more serious than the insecticides. Such problems that emanated from the utilization of synthetic herbicides cannot be overlooked regardless of the benefits accruing of its application [9, 12]. According to Williams et al. [10],the herbicide applied in agricultural lands can be leached and washed by rain or precipitation which leading to extending their risks to the wider areas which applied.

The herbicide effects on the soil and the environment were detected and found to contaminate the groundwater and the source of fresh drinking water even at recommended levels, causing an acute decrease in the biomass such as microorganisms, plant tissues and soil organic matter [13]. On the other hand, most of the synthetic herbicides not only affect the target plants, but it can also cause low growth rates, reproductive problems, changes in appearance or behavior or even death of non-target plant species, making the use of herbicides more harmful [14]. Furthermore, a wide range of non-targeted plant species are more sensitive to herbicides, especially during the reproductive stages of their life cycle. This is further compounded by the effect of external factors such as wind and rainfall, which can adversely affect this most important stage of the plant's life cycle. In this regard, Boutin et al. [15] mentioned the delays in flowering and reduction in seed production observed in a large number of non-target plant species, including climbing and hedgerow plants, through the spraying of herbicides within the vicinity of their growing locations.

3. Development of weed resistance to synthetic herbicides

Weed resistance to synthetic herbicides is considered to be the most difficult problem facing weed chemical control. The resistance comes when some of the weed species to be resistant to the herbicides naturally. Weed resistance can come in different forms. One of the mechanisms is through the production of a new generation of weeds of different morphological and physiological characteristics with shorter life cycles that can survive from the application of the systemic herbicides. Thus, the number of these weeds surviving from the continuous application of herbicides which will gradually increase. While the other weed species in the same area will be controlled by applying herbicides [16]. Another way in the development of weed resistance comes from the application of contact herbicides, which are responsible for inhibiting the process of photosynthesis, such as attrition. The application of such herbicides, especially during unfavorable weather conditions can contribute to the absorption of a small amount of the active ingredient but ineffective to the targeted weeds. Over time, the continuous accumulation of contact herbicides developed a new generation of weed that is immune to the synthetic herbicides [17]. In September 2010, Dow AgroSciences' scientists stated that weeds which have become resistant to the glyphosate herbicide and the ensuing production of genetically modified plants are one of the solutions to resolve issues pertaining to weed competition [7]. Nowadays, there are more than 604 species of weed plants considered as resistance to synthetic herbicides, most of these weed species are resistant to herbicides which are responsible for inhibiting acetolactate synthase (ALS enzyme), photosystem II and acetyl-CoA carboxylase [18, 19]. **Figure 1**, showed the number of resistant plant species for several herbicides according to their modes of action [18].

In this regard, Sekutowski [20] and Weber and Golebiowska [21] reported that there are 10 species of weeds that pose the biggest threat to crops by causing yield losses. The weeds include the most important herbicide-resistant species which are characterized by multiple resistances such as rigid rye-grass (*Lolium rigidum* Gaud.), wild oat (*Avena fatua* L.) and redroot pigweed (*Amaranthus retroflexus*). As a result of weed resistance, many types of synthetic herbicide are re-evaluated as useless. Hence, a lot of conventional herbicides have been identified as resistance and ineffective against common weeds. For example, there are 116 useless conventional herbicides identified in Europe, where the highest number of herbicides is found in France (30 types) followed by Spain (26 types), United Kingdom (24 types), Belgium (18 types) and Germany (18 types) [22].

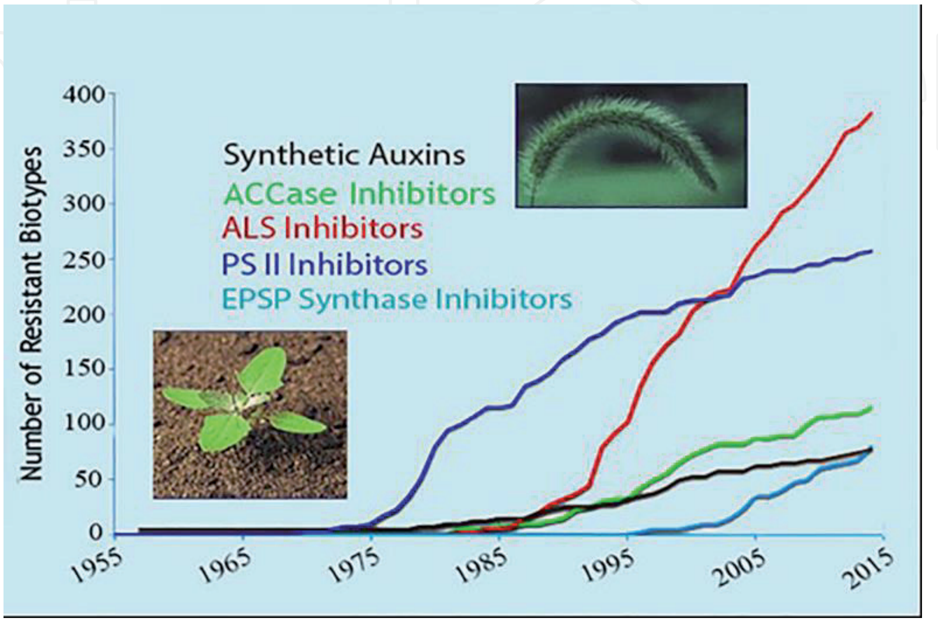

Figure 1.
Number of resistant plant species for several herbicides according to their modes of action [18].

Therefore, due to the similarity of the active ingredient in most of the herbicides that belong to the same group, there is no major new site-of-action herbicide has been introduced into the marketplace in the last two decades [23]. Conditions for the registration of synthetic herbicides also become strict and complicated. This is considered the greatest loss in the herbicides production sector. For example, the number of new herbicides active substances in Europe declined to 336 in 2009 from 945 in 1999 [23]. In fact, chemical herbicides development efforts worldwide whose market used to be monopolized by glyphosate-based herbicide have diminished since 1996 as a result of the glyphosate-resistant which is considered the most widely used pesticide in the world [24]. Therefore, the trend today is toward the use of natural alternative compounds, but still possess their herbicidal potential and safety versus the currently used synthetic and non-ecofriendly materials, wherein the plant defense tactic characterized by plant secondary metabolites, come to the forefront as promising solutions to replace the conventional herbicides.

4. Allelopathic compounds

The word allelopathy comes from the Greek words "Allelon" meaning "each other" and "Pathos" refers "to suffering". This allelopathic phenomenon whereby a plant response in defense of the neighboring plants, insects, microorganism and animals results in the production of natural chemicals called allelochemicals or phytochemicals [25, 26]. Allelopathy phenomenon is defined by Kato-Noguchi [27] as an important defense mechanism of the plant which results in the manufacturing of secondary metabolites. This term is also defined by the International Allelopathy Society in 1996th as a science that study any process involving secondary metabolites produced by plants, micro-organisms, viruses, and fungi that influence growth and development of agricultural and biological systems, excluding animals [28]. Usually, the allelochemical compounds released from donor plants caused negative effects on organisms found within the surrounding environment. However, some of the recent researchers reported the effects of the allelochemical produced by plants belonging to the plant family (Fabaceae) can be positive to the surrounding environment. As for an instance, the allelochemicals residues produced by these plant types such as legumes help to fix nitrogen from the air thus enriching the soil [29]. Most of the plants including weeds release allelochemical compounds as defense mechanisms. These compounds can be released from donor plant parts into the environment by leaching, volatilization, exudate from living plant tissue or by the decomposition of plant residues as shown in **Figure 2**. Hence, it was responsible for inhibiting the germination and growth of neighboring organisms [30]. One of the major advantages of allelopathy involves the release of plant biochemical compounds into the environment that inhibits germination or suppresses the growth of the surrounding vegetation. Another form of allelopathic potential can be tapped from trees that produce biochemical compounds for its survival and hence its reproduction. An example of such plants is eucalyptus; these types of plants can be used in agricultural production as cover crops to control weeds [31]. Lately, the allelopathic phenomenon has gained prominent attention and has been successfully employed in field crop production toward the improvement of crop productivity and for the protection of the environment through eco-friendly control of weeds, pests and crop diseases [32, 33].

The motivation for the use of the allelochemical compound in weed control is attributed to its phytotoxic effects similar to the phytotoxic effects of the synthetic herbicides in inhibiting seed germination and reducing seedling growth. The

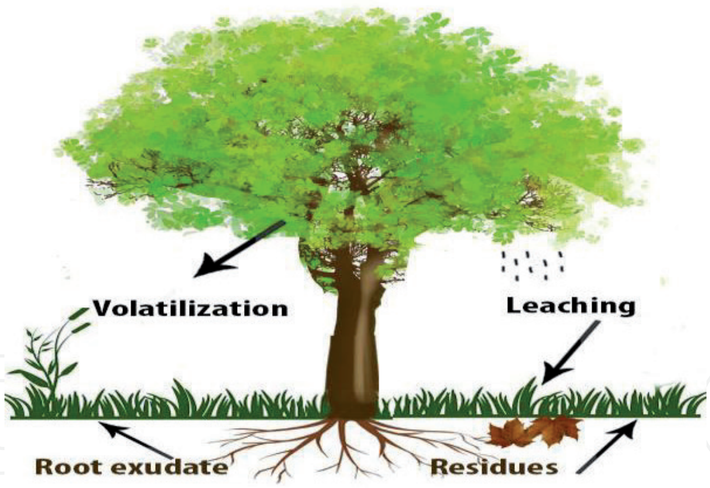

Figure 2.
Methods of allelochemical compounds released from the donor plant into the environment.

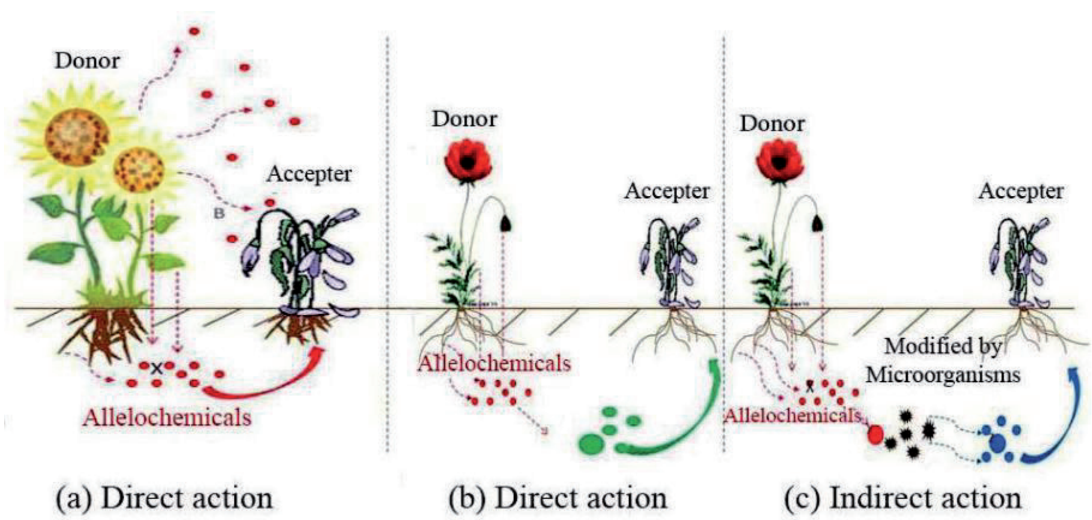

Figure 3.
Direct and indirect allelopathic mechanisms of donor plant to the targeted plants [19].

inhibition process includes several action sites such as cell division, nutrient uptake, photosynthesis and specific enzymatic functions [34]. The benefit of using allelopathy will not be just from being an attractive alternative to conventional herbicides, but also in the possibility of applying at places where the use of synthetic herbicides is illegal such as in organic farming. Thus, the use of allelochemical compounds could be adopted to reduce damage resulting from weed competition of the areas where the use of synthetic herbicides is not allowed [35]. Plants produce secondary metabolites exhibited a few ecological advantages such as pollinator attractants, determinants of vegetation patterning, provide protection against predators and other enemies and more importantly in mediating plant-plant interactions known as allelopathy [36]. The responsible chemical compounds for demonstrating allelopathic influences are called allelochemicals or biochemicals compounds produced as offshoots from the primary metabolic pathways of plants [37].

Allelochemicals have been defined as compounds derived as metabolic by-products of that certain plant which, when introduced into the environment can cause growth inhibition as a result of different malfunctions inside targeted plants such as respiration, cell division, water and nutrient uptake. The symptoms of the "allelopathic effects" include leaf wilting and yellowing, or death of part or all of a plant [3]. Allelochemical compounds, therefore, can act directly and indirectly when releasing from donor to the receiver plant as described in **Figure 3** which showed the direct and indirect allelopathic mechanisms of donor plant to the targeted plants [19]. The direct action of allelochemicals similar to the action of conventional herbicides hence may lead to being a new approach in herbicides technique to discover and select the most effective allelopathic plants which are the commonly used as natural herbicides [24]. The allelopathic potential on targeted or receiver plants are shown in different ways, such as the reduction in both the length and mass of radicle and roots, extension shoot and coleoptile, swelling or necrosis of root tips, destruction of cell wall, curling of the root axis, lack of root hairs, decrease in the number of seminal roots, reduced in plant dry weight accumulation, leaf discoloration and lower in reproductive capacity [25, 33, 38]. Allelopathic inhibition is complex and can involve the interaction of different classes of allelochemicals such as phenolics, flavonoids, terpenoids, alkaloids, steroids, carbohydrates and amino acids [37, 39].

The allelopathic mechanisms of allelochemical compounds on targeted plants that have been identified by Li et al. [40] can be summarized as below:

1. Changes in membrane permeability and inhibition of plant nutrient uptake.

2. Inhibition of cell division, elongation, and submicroscopic structure.

3. Effects on plant photosynthesis and respiration.

4. Effects on various enzymatic functions and activities.

5. Effects on the synthesis of plant endogenous hormones.

6. Effects on protein synthesis.

Allelochemical compounds have been classified into 10 categories depending on the structures and properties of these compounds according to [22, 40] namely the flavonoids, terpenoids, alkaloids, phenolics, tannins, coumarins, cinnamic acid and its derivatives, simple lactones, water-soluble organic acids and long-chain fatty acids. A wide range of these biochemicals are synthesized through the shikimate pathway or the isoprenoid pathway which are responsible for the essential oil production [41].

5. Essential oils

Essential oil is a concentrated volatile liquids consisting of different types of secondary plant metabolites but mainly composed of terpenoids and phenolics. Technically, essential oils are defined as odiferous bodies by oily nature obtained from plants by different ways, such as cold and hot pressing, distillation and extraction using organic solvents [42].

Essential oils produced from specific types of plants can be used for different purposes. Most of the essential oil usage is influenced by donor or producer plants and their surroundings such as scent to attract certain animals and insects, aiding in pollination, protection or as repellent agents, energy reserve, wound healing and prevent water evaporation. Essential oils can be obtained from different parts of plants such as the leaves, flowers, fruit, seeds, roots, rhizomes, bark and wood [43].

Biosynthetically, essential oil components composed of two groups. The first group is the terpenoids, which is considered the main group; mostly, of the monoterpenoids, sesquiterpenoids. The second group is non-terpenoids, which may contain aromatic compounds such as phenylpropanoids, short-chain aliphatic structures, nitrogenated and sulfuric substances [42]. Essential oils can be isolated from plants by several processes such as expressed oils, steam distillation, solvent extraction, fractional distillation and percolation and carbon dioxide extraction. The process of steam distillation is the most widely accepted method for the extracting of essential oils on a large scale.

The steam distillation process considered lower risk as compared with another process due to absence chemical compounds such as solvents and the thermal degradation as temperature generally not above 100°C [42]. Considering the multiple properties demonstrated with essential oils, such as pharmaceutical applications, antioxidant, food and cosmetic uses [44, 45]. Nowadays, essential oils are becoming increasingly important as a safer alternative to synthetic chemical products [46]. Essential oils also showed a broad spectrum of advantages against the pest, plant pathogenic and fungi ranging from bactericidal, fungicidal, insecticidal, antifeedant or repellent, oviposition deterrent, and growth regulatory and antivector activities [47, 48]. The application of essential oils and their constituents mainly; terpenoids for weed and pest management is currently being explored and is viewed as an important source of lead molecules in agriculture [49, 50].

Recently, the effectiveness of essential oils has been investigated on some weed species, demonstrating the ability to inhibit germination and the development of seedlings. The reasons that encouraged the use essential oils as alternative compounds to conventional herbicides are due to a less harmful effect on the environment and almost as effective as the synthetic herbicides. Furthermore, there are no contradictions and obstacles to be used as bioherbicides in all aspects of agriculture, specifically in organic farming as compared to the use of synthetic pesticides, which has attracted a lot of interest in the safety and health of the consumers [35].

6. Terpenoids

Terpenoids or terpenes are the most structurally varied classes and they are the largest family of compounds of plant products. Previous studies estimated the exiting of more than 23,000 of known terpenoid compounds, including carotenoids, tocopherol, phytol, steroids and hormones [51]. Terpenoids play an important and essential role in a broad range of biological functions like respiration, chain electron transport, cell wall and membrane biosynthesis. Also, terpenoids are involved extensively in the fields of pharmaceuticals, cosmetics, colorants, disinfectants, scents, flavorings and agrichemicals [52]. Biosynthetically, terpene compounds are classified as unsaturated hydrocarbons and basically synthesized from the isoprene unit which has the molecular formula ($CH_2{=}C(CH_3){-}CH{=}CH_2$). The molecular formulae of terpenoids are multiples of that, (C5H8) and where (n) is the number of linked isoprene units called the isoprene rule or the C5 rule; **Figure 4** shows the chemical structure of the isoprene unit.

The isoprene units may be joined together head-to-tail to form linear chains or they may be arranged to form rings. Chains of isoprene units are linked to building the terpene structure that synthesized sequentially to form hemiterpenes, monoterpenoids, sesquiterpenoids, diterpenes, sesterterpenes, triterpenes, and tetraterpenes depending on the number of isoprene units [53].

Terpenoids play a defensive role in trees. They are the major component of essential oils in many trees which are responsible for the aroma of the trees. They are released into the air by vaporization or leached in small amounts by water. These compounds caused poor growth of neighboring plants in addition to aggravating other problems site when released [54]. Among the terpenoids compounds, Monoterpenoids and sesquiterpenoids are the most available compounds in the secondary plant metabolites and widely used as antimicrobials and cosmetics. Monoterpenoids and sesquiterpenoids produce in plants as defensive chemicals against insects, fungi and surrounding plants [51].

Terpenoids can be classified according to the number of isoprene units in the molecule. A prefix in the name indicates the number of terpene units needed to assemble the molecule; **Table 1** lists of various classifications of isoprene units as well as the examples of the compounds associated with the classification. All the above different secondary plant metabolites are produced through the metabolism of primary metabolites depending on the pathway and the type of primary metabolites.

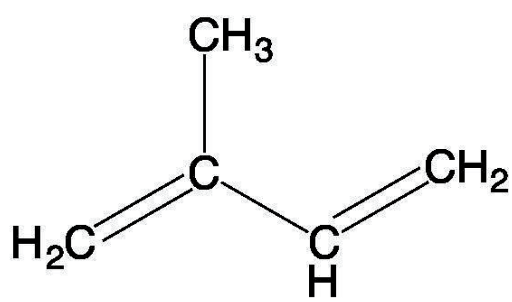

Figure 4.
Structure of one isoprene unit.

No.	Type of classification	Number of isoprene units	Structure formula	Example
1	Hemiterpenes	Single	C_5H_8	Prenol and isovaleric acid
2	Monoterpenoids	Two	$C_{10}H_{16}$	Geraniol, limonene, terpineol and myrcene
3	Sesquiterpenoids	Three	$C_{15}H_{24}$	Humulene, caryophyllene, and farnesol
4	Diterpenoids	Four	$C_{20}H_{32}$	Cafestol, kahweol, cembrene and taxadiene and phytol
5	Sesterterpenoids	Five	$C_{25}H_{40}$	Geranylfarnesol
6	Triterpenoids	Six	$C_{30}H_{48}$	Sterols
7	Sesquarterpenoids	Seven	$C_{35}H_{56}$	Ferrugicadiol and tetraprenylcurcumene
8	Tetraterpenoids	Eight	$C_{40}H_{64}$	Cyclic lycopene, carotenoids
9	Polyterpenes	More than eight	—	Natural rubber

Table 1.
Classification of terpenoids based on the number of isoprene units.

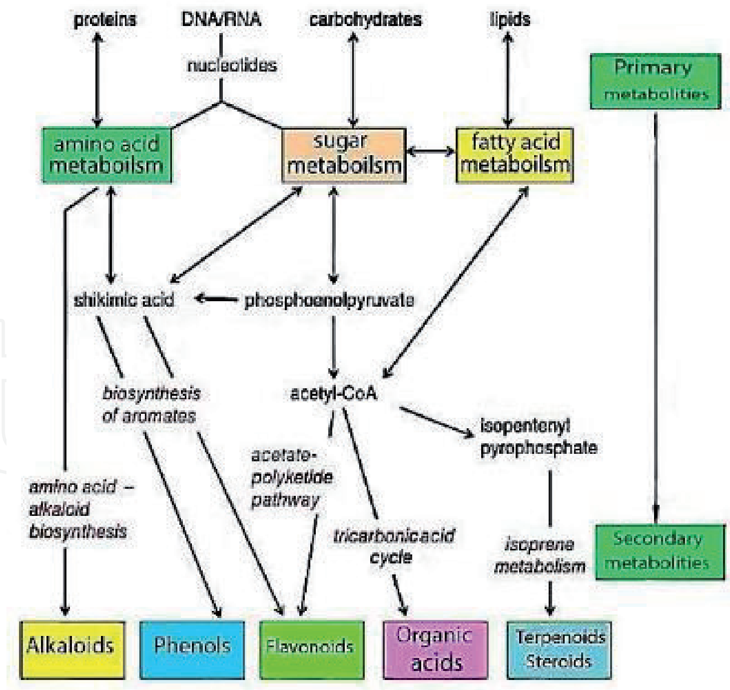

Figure 5.
General schematic biosynthetic pathways to produce major secondary metabolites including terpenoids [60].

6.1 Biosynthesis of terpenoids

Secondary metabolites including terpenoids are derived essentially from the modification of primary metabolites by different main pathways; the pathways responsible for synthesizing the primary metabolites. The secondary metabolite biosynthetic pathways are too numerous and cannot be easily determined. Nevertheless, there are a few typical pathways involved in the biosynthesis of major classes of these compounds. The shikimate pathway is considered the major pathway used by plants as well as different organisms like bacteria and fungi to synthesize primary metabolites which in turn form the basic building block for a wide range of phenolic and flavonoid compounds [55, 56]. The shikimate pathway involving multiple isoprene units (C_5H_8) linked together in a head-to-tail pattern can synthesize to terpenoids according to the number of isoprene units incorporated in the molecular skeleton [57]. Terpenoids can also be synthesized through an isopentenyl diphosphate pathway, which arose from the intermediate substrate, particularly, mevalonic acid (MVA) via the mevalonate pathway and a methylerythritol phosphate/deoxy-D-xylulose 5-phosphate pathway (MEP/DOXP) pathway. **Figure 5** showed the biosynthesis of terpenoids [58, 59].

7. Terpenoids as natural weed killers; mode of action

The term "mode of action" refers to the sequence of herbicides action beginning from absorption by plant tissues until death. Understanding herbicide mode of action is helpful in knowing what groups of weed killers. Generally, herbicides classified depending on their mode of action and the toxicity into two groups; contact and systemic herbicides [56]. Contact herbicides only kill the plant tissue which comes into contact with the spray solution. While systemic herbicides need to translocated in plant tissues until reaching the active site for causing the injury. Contact herbicides quite often the fastest acting by causing acute toxicity but the whole plant must be sprayed to be effective [60]. Herbicides also can further classify according to their selectivity to selective or non-selective herbicides. Non-selective herbicides can kill most plants while selective herbicides designed to kill specific types of plants depends on the morphological and physiological differences between the two major plant groups, grassy or broadleaf. Moreover, herbicides can be divided into two groups as a result of its application timing; pre and postemergence. Preemergence herbicides normally targeted seeds by preventing the germination and suppress seedling development. While postemergence herbicides target weed biomass by reducing or inhibiting the biological processes in plant tissues.

Study of the injury symptoms of the targeted plant tissues resulting from the application of herbicides helps to determine how herbicides interact with the biological and physical systems of the targeted plant. Injury symptoms in targeted weed species depend on the type of herbicide, the rate of application, stage of growth, type of exposure, and the plant species receptor involved. All herbicides work by disrupting one or more than one of the natural mechanisms of the targeted plant tissues such as the stomatal system through the influence of the guard cells, photosynthesis by the distraction of chlorophyll pigment and targeting cell membrane and other cellular systems.

Herbicidal mechanisms of the secondary plant metabolites as post-contact formulations weed killers are strictly fast-acting. They generally disrupt the cuticular layer of the foliage which resulting in the rapid desiccations or burndown of young tissues [35]. Membrane disruption can be considered as one of the underlying mechanisms of plants' phytotoxic effects, which result in cell death and growth inhibition. Secondary metabolites such as terpenoids are less specific and attack a multitude of proteins by building hydrogen, hydrophobic and ionic bonds and as a result of this, modulating their 3D structures and in consequence their bioactivities [61] (**Figure 6**).

Monoterpenes are considered lipophilic compounds; hence, there is, therefore, the possibility of plant cell membrane expansion as a result of accumulation monoterpenes, thereby destroying the membrane structure [62, 63]. **Figure 7** showed the interaction of terpenoids with the plant cell membrane [64]. Moreover, the monoterpenes compounds in essential oils uncoupled the oxidative photophosphorylation (transform ADP to form ATP using the energy of sunlight). As a result, monoterpenes cause a reduction in cellular respiration leading to a perturbation in the ATP production. Thus, disorders in physiological processes in plants are induced [33, 65] (**Table 2**).

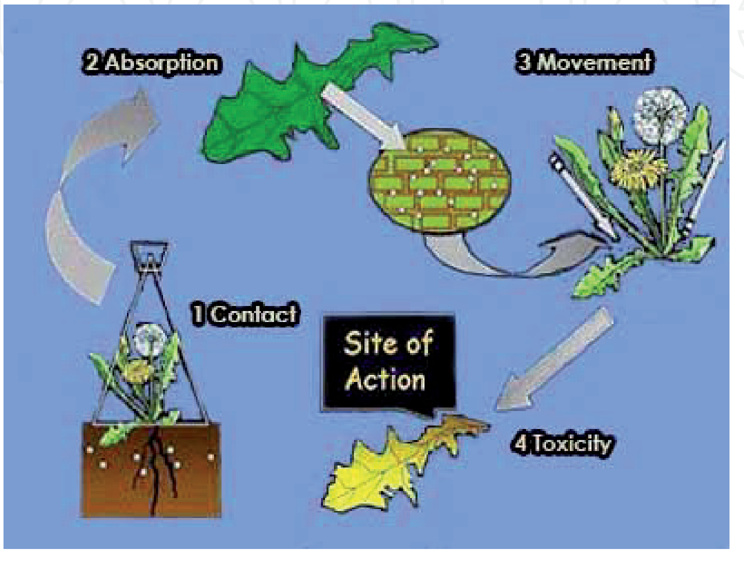

Figure 6.
Natural weed killers; mode of action [23].

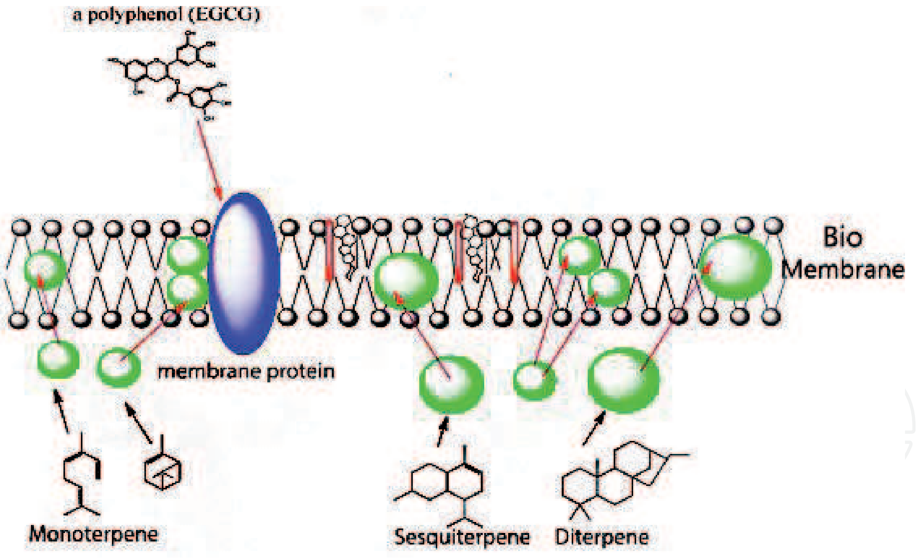

Figure 7.
Interaction of terpenoids with plant cell membrane [60].

Donor plant	Involved terpenoid compounds	Affected weed species	Ref.
Artemisia scoparia	p-Cymene Caryophyllene Germacrene D Limonene α-Pinene	*Achyranthes aspera,* *Cassia occidentalis* *Parthenium hysterophorus* *Echinochloa crus-galli,* *Ageratum conyzoides*	[26]
Nepeta meyeri	Nepetalactone	*Amaranthus retroflexus* *Portulaca oleracea* *Bromus danthoniae,* *Agropyron cristatum* *Lactuca serriola* *Bromus tectorum* *Bromus intermedius* *Chenopodium album* *Cynodon dactylon* *Convolvulus arvensis*	[66]
Leptospermum scoparium		*Digitaria sanguinalis*	[35]
—	Limonene	*Amaranthus viridis* L	[67]
Peumus boldus	Ascaridole p-Cymene 1,8-Cineole	*Amaranths hybrids* *P. oleracea*	[68]
Anisomeles indica	α-Bisabolol oxide	*Bidens pilosa* *C. occidentalis,* *A. viridis* *E. crus-galli*	[69]
Cistus ladanifer	Trans-pinocarveol Viridiflorol Bornyl acetate Ledol	*A. hybridus* *Conyza canadensis* *Parietaria judaica*	[50]
Eucalyptus salubris	1,8-Cineole α-Pinene ρ-Cymene Predominant	*Solanum elaeagnifolium*	[70]
Cupressus sempervirens	α-Pinene α-Cedrol δ-3-Carene Germacrene D	*L. rigidum* *Phalaris canariensis* *Trifolium campestre* *Sinapis arvensis*	[71]

Donor plant	Involved terpenoid compounds	Affected weed species	Ref.
Pinus pinea	Limonene α-pinene β-Pinene	*S. arvensis* *Trifolium campestre* *L. rigidum* *P. canariensis*	[72]
N. meyeri	Nepetalactone	*Bromus danthoniae* *Lactuca serriola*	[73]
Eucalyptus globulus	1,8-Cineole	*Amaranthus blitoide* *C. dactylon*	[74]
Cymbopogon citratus	Citral	*E. crus-galli*	[64]
Satureja khuzestanica *Satureja rechingeri*	Carvacrol Thymol	*Secale cereale*	[75]
Pinus brutia *Pinus pinea*	α-Pinene β-Pinene	*L. sativa* *Lepidium sativum* *P. oleracea*	[76]
Eupatorium adenophorum	γ-Cadinene γ-Muurolene	*Phalaris minor*	[77]
Pelargonium graveolens	Citronellol Geraniol	*Silybum marianum*	[78]
Artemisia judaica	Thujone Chrysanthenone	*S. marianum*	
Carum carvi	Carvone Limonene	*Phalaris canariensis*	[79]
Thymus daenensis	Thymol Carvacrol	*A. retroflexus* *Avena fatua* *Datura stramonium* *Lepidium sativum*	[80]
Eucalyptus citriodora	Citronellol	*A. viridis*	[67]
Plectranthus amboinicus	Carvacrol Thymol	*L. sativa* *Sorghum bicolor*	[81]
Tagetes minuta	Limonene piperitenone α-terpinolene Piperitone (E)-Tagetone (Z)-Ocimenone	*Chenopodium murale* *Ph. minor* *A. viridis*	[82]
Cupressus macrocarpa	Citronellal Thujene Thymol	*Digitaria australe* *A. hybridus*	[83]
Pelargonium radula	Cis-Geraniol Eudesmol	*Digitaria australe* *A. hybridus*	
Melaleuca bracteata	Methyl eugenol	*Panicum virgatum* *D. longiflora* *Stachytarpheta indica* *Aster subulatus*	[84]
C. citratus	Neral Geranial	*P. virgatum* *Chloris barbata,* *Euphorbia hirta* *Stachytarpheta indica*	[85]
Eucalyptus lehmannii	1,8-Cineole α-Thujene α-Pinene	*Sinapis arvensis* *Diplotaxis harra* *Trifolium campestre* *Desmazeria rigida* *Phalaris canariensis*	[86]

Donor plant	Involved terpenoid compounds	Affected weed species	Ref.
Eucalyptus cinerea	1,8-Cineole α-Pinene ρ-Cymene α-Terpineol	*S. arvensis* *Erica vesicaria* *Scorpiurus muricatus*	[87]
Nepeta cataria	Nepetalactone	*Hordeum spontaneum* *Taraxacum officinale* *Avena fatua*	[88]
Pinus nigra	Germacrene D δ-Cadinene Caryophyllene	*P. canariensis* *Trifolium campestre* *S. arvensis*	[89]
Zanthoxylum piperitum	Xanthoxyline	*Amaranthus tricolor*	[90]
Satureja montana	Carvacrol Thymol	*P. oleracea* *Lolium multiflorum* *E. crus-galli*	[91]
Eucalyptus citriodora	Citronellal Citronellol	*S. arvensis* *Sonchus oleraceus* *Xanthium strumarium* *A. fatua*	[92]
Copaifera duckei *Copaifera martii* *Copaifera reticulata*	Germacrene-D β-Caryophyllene, α-humulene, δ-elemene, and δ-cadinene	*Mimosa pudica L.* *Senna obtusifolia*	[93]

Table 2.
Allelopathic effects of terpenoids compounds in essential oils on seed germination and seedling development on different weed species 2010–current.

8. Conclusion

In this chapter, we presented a detail overview about roles of terpenoids in essential oils as a natural weed killer on a wide range of weed species according to the latest investigations conducted in the current decade. Terpenoids can be useful to control weeds which should be considered as a new approach agricultural sustainable to reduce weed losses and keeping the environment safe from the risks of synthetic herbicides. The current review also turns out that monoterpenoids showed the highest phytotoxicity in comparison to the sesquiterpenoids when these types considered the dominant compounds found in essential oils.

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